agronomy

Review

Prospects of Bioenergy Cropping Systems for A More Social-Ecologically Sound Bioeconomy

Moritz Von Cossel [1,*], Moritz Wagner [1], Jan Lask [1], Elena Magenau [1], Andrea Bauerle [1], Viktoria Von Cossel [2], Kirsten Warrach-Sagi [2], Berien Elbersen [3], Igor Staritsky [3], Michiel Van Eupen [3], Yasir Iqbal [4], Nicolai David Jablonowski [5,6], Stefan Happe [7], Ana Luisa Fernando [8], Danilo Scordia [9], Salvatore Luciano Cosentino [9], Volker Wulfmeyer [2], Iris Lewandowski [1] and Bastian Winkler [1]

[1] Biobased Products and Energy Crops (340b), Institute of Crop Science, University of Hohenheim, Fruwirthstr. 23, 70599 Stuttgart, Germany; mowagner@uni-hohenheim.de (M.W.); jan.lask@uni-hohenheim.de (J.L.); elena.magenau@uni-hohenheim.de (E.M.); a.bauerle@uni-hohenheim.de (A.B.); iris_lewandowski@uni-hohenheim.de (I.L.); b.winkler@uni-hohenheim.de (B.W.)

[2] Institute of Physics and Meteorology (120), University of Hohenheim, Garbenstr. 30, 70599 Stuttgart, Germany; vikoca@web.de (V.V.C.); kirsten.warrach-sagi@uni-hohenheim.de (K.W.-S.); volker.wulfmeyer@uni-hohenheim.de (V.W.)

[3] Earth Informatics, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands; berien.elbersen@wur.nl (B.E.); igor.staritsky@wur.nl (I.S.); michiel.vaneupen@wur.nl (M.V.E.)

[4] College of Bioscience and Biotechnology, Hunan Agricultural University, Changsha 410128, China; yasir.iqbal1986@gmail.com

[5] IBG-2: Plant Sciences, Institute of Bio- and Geosciences, Forschungszentrum Jülich, 52425 Jülich, Germany; n.d.jablonowski@fz-juelich.de

[6] Bioeconomy Science Center (BioSC), c/o Forschungszentrum Jülich, 52425 Jülich, Germany

[7] Institute of Animal Breeding and Husbandry, Kiel University, Olshausenstr. 40, 24098 Kiel, Germany; stefanhappe78@gmail.com

[8] MEtRICs, Departamento de Ciências e Tecnologia da Biomassa, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus de Caparica, 2829-516 Caparica, Portugal; ala@fct.unl.pt

[9] Dipartimento di Agricoltura, Alimentazione e Ambiente (Di3A), University of Catania, 95123 Catania, Italy; dscordia@unict.it (D.S.); sl.cosentino@unict.it (S.L.C.)

[*] Correspondence: moritz.cossel@uni-hohenheim.de; Tel.: +49-7114-592-3557

Received: 29 August 2019; Accepted: 30 September 2019; Published: 2 October 2019

Abstract: The growing bioeconomy will require a greater supply of biomass in the future for both bioenergy and bio-based products. Today, many bioenergy cropping systems (BCS) are suboptimal due to either social-ecological threats or technical limitations. In addition, the competition for land between bioenergy-crop cultivation, food-crop cultivation, and biodiversity conservation is expected to increase as a result of both continuous world population growth and expected severe climate change effects. This study investigates how BCS can become more social-ecologically sustainable in future. It brings together expert opinions from the fields of agronomy, economics, meteorology, and geography. Potential solutions to the following five main requirements for a more holistically sustainable supply of biomass are summarized: (i) bioenergy-crop cultivation should provide a beneficial social-ecological contribution, such as an increase in both biodiversity and landscape aesthetics, (ii) bioenergy crops should be cultivated on marginal agricultural land so as not to compete with food-crop production, (iii) BCS need to be resilient in the face of projected severe climate change effects, (iv) BCS should foster rural development and support the vast number of small-scale family farmers, managing about 80% of agricultural land and natural resources globally, and (v) bioenergy-crop cultivation must be planned and implemented systematically, using holistic approaches. Further research activities and policy incentives should not only consider the economic potential of bioenergy-crop cultivation, but also aspects of biodiversity, soil fertility, and climate change adaptation specific to site conditions and the given social context. This will help to adapt existing agricultural systems in a changing world and foster the development of a more social-ecologically sustainable bioeconomy.

Keywords: biodiversity; bioeconomy; bioenergy crop; biomass; carbon capture; climate change adaptation; cropping system; industrial crop; marginal land; resilience

1. Introduction

At the 27th European Biomass Conference and Exhibition in Lisbon, there was a broad consensus that crop-based biomass is crucial for supporting a growing European bioeconomy [1]. Biomass from bioenergy crops is seen as a key element in the achievement of climate change mitigation strategies such as carbon sequestration and bioenergy with carbon capture and storage (BECCS) [2–5]. Today, most bioenergy crops are C3 and C4-plant species. Additionally, plant species with the crassulacean acid metabolism (CAM) such as the pencil tree (*Euphorbia thirucalli* L.) [6–9], prickly pear (*Opuntia ficus-indica* (L.) Mill. [10,11] and agave (*Agave tequilana* F.A.C.Weber) [12,13] have the potential for resilient bioenergy cropping systems (BCS) in drought-affected sites [14]—especially in the Mediterranean agroecological zone. However, crop-based bioenergy has stagnated over the last five years [1,15]. This is problematic in view of the EU's ambition to reduce greenhouse gas (GHG) emissions by 40% by 2030 [16]. Of all renewable energies, biomass-based energy plays the most important role in power-to-X pathways [17], in particular, bio-based transportation fuels [18–21]. Together with electricity and hydrogen, biofuels are crucial for the decarbonization of the transport sector [18,19,21–25]. The use of bioenergy crops, crop residues, and organic civilization wastes as co-substrates in biogas plants could also be of significance in renewable energy production [26–29]. Further, bio digestion enables the efficient use of liquid manure for biogas production and, at the same time, the reduction of nitrous oxide emissions from manure [30,31], especially in organic farming systems [30,32]. However, there are various other utilization pathways for crop-based biomass beyond bioenergy, including biomaterials and biochemicals produced through biorefinery and cascading use concepts [33–36]. Increasing competition in biomass usage could have a negative impact on the bioenergy sector whenever it is more feasible to follow biorefinery or cascading use concepts than to simply produce bioenergy from biomass [33]. Increasing pressure on land use due to the food, energy, and environment trilemma [18,37–43] will further intensify competition between the production of industrially useable biomass for the growing bioeconomy and the rising demand for food and bioenergy. Thus, it remains unclear how bioenergy crops could significantly contribute to the achievement of the European Renewable Energy Directive II.

Consequently, when cultivating bioenergy crops, potentially adverse effects on food security need to be taken into consideration, on both a global and, in particular, local level [37,44,45]. This pressure on food security mainly applies to first-generation bioenergy crop cultivation on good arable soils [45–50]. As far as marginal agricultural land is concerned, the land use conflict with food crop cultivation is low [42,49,51–54]—indicating great bioenergy potential in these areas. Here, marginal agricultural land is defined as 'lands having limitations which, in aggregate, are severe for the sustained application of a given use, and/or are sensitive to land degradation as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention' [55]. The limitations include a number of biophysical constraints such as adverse rooting conditions, contamination, and salinity [51]. Particularly because of the latter limitations, such sites are theoretically appropriate for biomass production because they are not suitable for food and feed production [56]. Worldwide, the estimated area of marginal agricultural land available for bioenergy crop cultivation amounts to approximately 7 Mm^2 [57]. A high proportion of this area could be used for the cultivation of lignocellulosic bioenergy crops (providing second-generation biofuels) such as miscanthus (*Miscanthus × giganteus* Greef et Deuter), giant reed (*Arundo donax* L.), switchgrass (*Panicum virgatum* L.), as well as low-input high-diversity grasslands [58–61] and short rotation coppices among others. Therefore, these lignocellulosic bioenergy crops theoretically hold a high biomass potential [57]. However, there are many social and ecological challenges for the implementation of this theoretical biomass potential, especially with regard to the accessibility of marginal agricultural land as well as biodiversity concerns [62,63]. In addition, inadequate land use for bioenergy crop production carries the risk of increasing rather than decreasing GHG emissions [45] and altering climatic conditions at the micro to regional level, as has been seen in massive deforestation at the global level (e.g., palm oil plantations) [64]. Thus, the potential impacts of bioenergy crop cultivation on biodiversity [39,50,65] and societal conditions [66,67] must be carefully considered for any type of land—as is also the case in the food crop cultivation sector [42,68]. This leads to numerous fundamental challenges for the future of bioenergy crop cultivation, including (i) land use conflicts with food-crop cultivation [43], (ii) land use conflicts with biodiversity conservation [69,70], and (iii) the suitability for low-input cultivation (to keep environmental impacts low) on marginal agricultural lands [51,71]. While there are two general approaches to tackling the limitation of land—land sharing (wildlife-friendly farming) [70,72] and land sparing [72]—many questions remain with respect to more sustainable bioenergy crop cultivation in the future.

Against this backdrop, the objective of this study to assess the potential contribution of bioenergy crop cultivation for a more sustainable bioeconomy, reviewing both climate change effects and the associated social-ecological challenges.

2. Potential Contribution of Bioenergy Crop Cultivation in a Changing World

There is broad consensus among scientists on the fact that the cultivation of bioenergy crops must be in line with the sustainable development goals (SDGs) [1,43,73,74]. Therefore, future bioenergy crop cultivation should fulfill the following requirements:

(1) Bioenergy crop cultivation should provide a beneficial social and ecological contribution, such as an increase of (agro-ecological) biodiversity and landscape aesthetics [58,75–77].
(2) Bioenergy crops should be cultivated on marginal agricultural land and thus present no competition to food crop production. Therefore, bioenergy crops have to be able to cope with the given biophysical constraints on marginal agricultural lands [51,55,78,79].
(3) Bioenergy cropping systems (BCS) need to be resilient towards the projected severe climate change effects [80–83].
(4) These BCS should foster rural development and support the vast number of small-scale family farmers, managing about 80% of the global agricultural land and natural resources [84].
(5) Accordingly, bioenergy crop cultivation must be planned and implemented systematically, and with the adoption of holistic approaches.

The following chapters describe how the potential BCS could fulfill these requirements.

2.1. The Potential Social-Ecological Contribution of Bioenergy Crop Cultivation

The utilization of marginal land is often linked to negative social-ecological impacts such as biodiversity losses, environmental pollution, and a decrease in the recreational value of the landscape [51,85]. This mainly applies to marginal forests and marginal high nature value areas (HNVs) which are accordingly considered unavailable for bioenergy crop cultivation. Conversely, the utilization of marginal agricultural land often promises to improve its overall value, or at least to maintain its current resilience and protect it from further degradation [55]. Many studies have revealed significant evidence to support the positive social-ecological effects of bioenergy crop cultivation on marginal agricultural land depending on the selected bioenergy crops and BCS, respectively [47,52,86–90]. Some dedicated bioenergy crops for cultivation on marginal agricultural land are shown in Figure 1. While some studies depict GHG emission savings [52,91], others have found that the best way of reducing

GHG emissions and storing CO_2 would be achievable through natural succession [92]. These and other relevant categories of social-ecological effects and impacts of bioenergy cropping will be discussed in the following sub-sections.

Figure 1. Impressions of some promising bioenergy/multi-purpose crops and their inflorescences: (**a**) yellow melilot (*Melilotus officinalis* L.) as part of a wild plant mixture for biogas production ('BG90', Saaten Zeller GmbH & Co. KG, Eichenbühl, Germany), (**b**) camelina (*Camelina sativa* L. Crantz), (**c**) hemp (*Cannabis sativa* L.), (**d**) cup plant (*Silphium perfoliatum* L.), (**e**) Virginia mallow (*Sida hermaphrodita* L. Rusby), and (**f**) miscanthus (*Miscanthus* × *giganteus* Greef et Deuter).

2.1.1. Bioenergy Crop Cultivation and Biodiversity

The task of protecting biodiversity has been acknowledged in the SDGs due to its central role in ecosystem functioning and human well-being [73,74]. According to the 'Convention on Biological Diversity' biological diversity is understood as the 'variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems' [93].

Bioenergy crop production influences biodiversity mainly through changes in land use (crop types and intensification) and land cover, which potentially result in habitat loss and fragmentation [93,94]. The large-scale deployment of bioenergy crops must therefore be carefully considered [95–97], which becomes apparent in the context of the wide-spread establishment of first generation bioenergy crops. There are clear indications that the intensive cultivation of annual energy crops such as maize or rape seed results in reduced species numbers due to a homogenization of landscape structures [95] (Figure 2). In comparison, results from small-scale and field-based studies have indicated that perennial bioenergy crops, such as miscanthus (Figure 1f), the cup plant (*Silphium perfoliatum* L.) (Figure 1d) [98], and willow (*Salix* spp.), provide positive, or at least less negative, impacts when compared with annual bioenergy crops [99–102]. However, the underlying implications for this are less obvious, and caution is required when making general assumptions. For instance, it has been shown that the impacts of the plantation of perennial crops may range from positive to even negative impacts on biodiversity compared to annual crops [97,103–107]. For example, miscanthus cultivation supports earthworm communities [89], but it does not provide nectar and pollen for pollinators as do wide crop rotations including flower-rich catch crops such as flax (*Linum usitatissimum* L.), lucerne (*Medicago sativa* L.) and *Phacelia* (*Phacelia tanacetifolia* Benth.) [108].

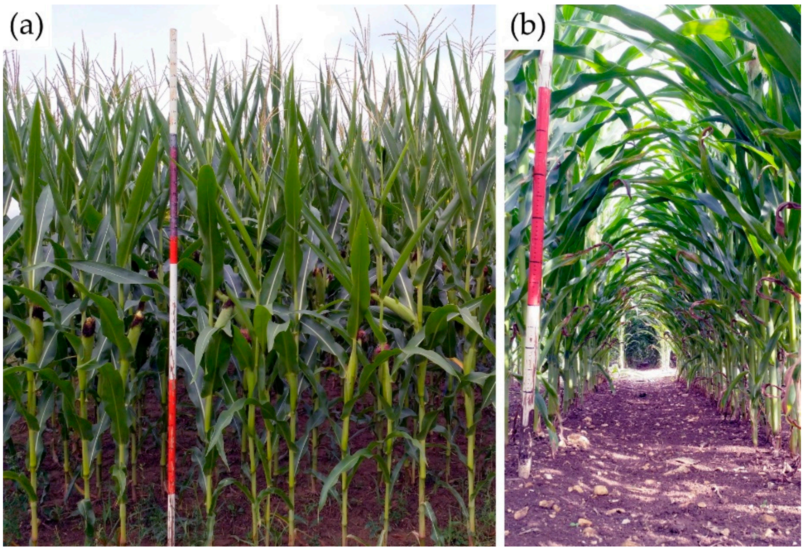

Figure 2. Mono-cropped maize (*Zea mays* L.) in Hohenheim (**a**) and Sankt Johann (**b**), Southwest Germany, August 2019.

The variation in results is a general concern with respect to the assessment of biodiversity in agricultural landscapes. Comparisons of studies are often challenging as the results depend strongly on the surrounding context, including the previous land use and a wide range of simultaneously acting factors (e.g., crop management, yield levels, pathogens, and the presence of plant growth-promoting organisms) [109]. This includes time-dependency, which is a particularly important issue for perennial bioenergy crops, as species dynamics may vary over time (from planting years to finally productive periods). Furthermore, assessment approaches focus mainly on the field-scale and only a few taxonomic groups, while functional aspects of the community composition as well as landscape considerations are only slowly beginning to receive more attention. Overall, these arguments emphasize the need for further methodological improvement in the field of biodiversity assessment.

The above mentioned aspects are equally relevant if marginal agricultural lands are considered for a future biomass and bioenergy supply [110]. In addition, comprehensive analyses of the inherent biodiversity potential of these areas are needed in order to understand the conditions under which these areas can be used sustainably for bioenergy production [96]. However, it is to be kept in mind that bioenergy crop cultivation on marginal agricultural land does not only pose a risk to biodiversity, but can also serve conservation efforts in this regard [95,111]. For instance, the spread of rapidly proliferating species on abandoned land could be counteracted by the cultivation of weed-suppressing perennial plants such as miscanthus, giant reed, cup plant and Virginia mallow (*Sida hermaphrodita* L. Rusby).

Clearly, the effects of bioenergy crop cultivation also depend strongly on agricultural management, which underlines the importance of the implementation of better management practices for future bioenergy crop deployment [96]. Perennial bioenergy crops could be strategically planted in arable farmland in order to act as corridors to connect habitat fragments, to stimulate landscape heterogeneity, and to provide additional ecosystem services [102,112–114]. Examples of potential management options are the establishment of bioenergy buffers and the integration of perennial plants into conventional bioenergy production systems [113,115]. Following these and further approaches, present agricultural landscapes could be diversified in order to enhance biodiversity and supply sustainable energy.

2.1.2. Spatial and Temporal Diversification of BCS

Agricultural diversification, i.e., the spatial and temporal diversification of BCS, has been intensively investigated over the past centuries, mainly according to agro-ecological farming practices such as intercropping [116], agroforestry [117–120], and polycultures [121]. Species-rich meadows [59] or perennial wild plant mixtures [88,122] are promising approaches to increase both the spatial and temporal diversity of BCS for biomass and bioenergy supply [76,108,123,124]. However, there are numerous other diversification approaches which are less intense but still relevant in terms of their social-ecologically aspects. For bioenergy crop cultivation, these less intense crop diversification approaches include:

(1) crop rotations [76,125–128],
(2) the intercropping of annual or perennial crops with legumes [86,129–132],
(3) the establishment of winter-annual species such as camelina (*Camelina sativa* L. Crantz) or perennial rye under annual crops [133–135], and
(4) under maize-establishment of perennial energy crops such as miscanthus [115], the cup plant [136], and wild plant mixtures [122] among others [76,108,123].

Therefore, agricultural diversification is a basic approach for increasing agrobiodiversity. The main aims of increasing agrobiodiversity are (i) the support for both insects and open land animals [137–141] and (ii) the resilience of the agroecosystem and, as such, climate change adaptation. Additionally, well-conceptualized agricultural diversification can help to optimize the agronomic performance of the BCS [108]. There are numerous factors and mechanisms that determine the agronomic effects of agricultural diversification within and between the plant stands (Figure 3). Furthermore, physiological traits such as drought tolerance, pest resistance, and nitrogen (N) use efficiency are of great importance to the support for agrobiodiversity, for example, through higher biomass production and the avoidance of pesticide applications [5].

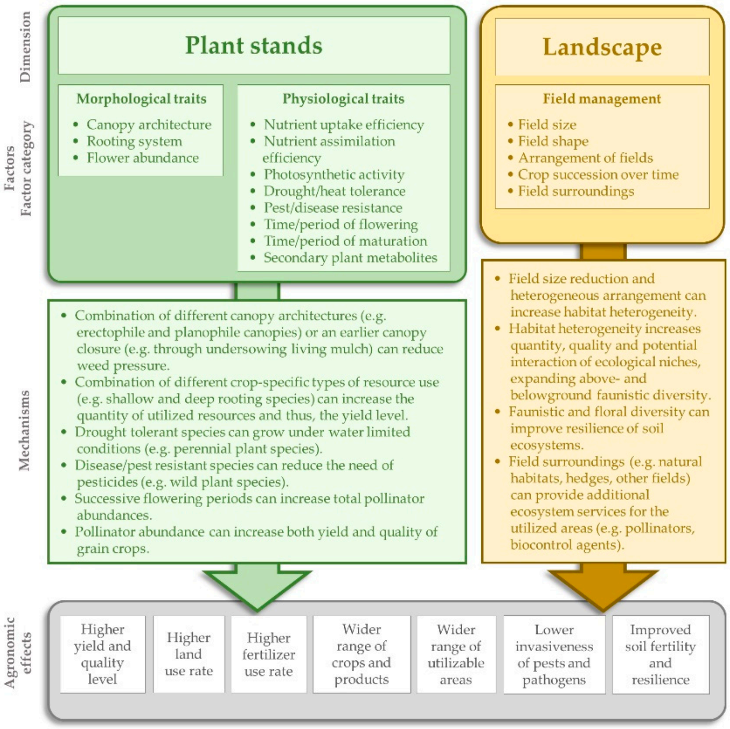

Figure 3. Factors and mechanisms potentially determining agronomic effects of agricultural diversification of bioenergy cropping systems both between (brown boxes) and within the plant stands (green boxes) (adapted from [109]). Note, that the agronomic effects (grey box) show the potential outcome for a best-case scenario.

For bioenergy crop cultivation, agricultural diversification can be achieved by including additional crops into the BCS such as camelina [134,142,143] (Figure 1b), kenaf (*Hibiscus cannabinus* L.) [144], hemp (*Cannabis sativa* L.) [145] (Figure 1c), lupin (*Lupinus mutabilis* Sweet) [51,146], velvetleaf (*Abutilon theophrasti* Medic.), [147] biomass sorghum (*Sorghum bicolor* L. Moench) [148], willow [149,150], cup plant [122,151,152] (Figure 1d), amaranth (*Amaranthus* spp.) [129,153], yellow melilot (*Melilotus officinalis* L.) (Figure 1a), and woad (*Isatis tinctoria* L.) [122,131]—insofar as a certain level of growth suitability within the respective regions is given [51]. The higher the landscape heterogeneity, the better the overall ecological performance [108,154]. Further, the benefits are highly context-dependent, subject to both site- and region-specific aspects such as temporal and spatial habitat networking [155] and the given ecosystem conditions [156]. Moreover, some bioenergy crops can also contribute to more pollinator-friendly agriculture on marginal agricultural lands. This holds true for annual bioenergy crops such as camelina (Figure 1b) and crambe (*Crambe abyssinica* Hochst Ex Re Fries), because (i) they are not very demanding and suitable for several types of marginal agricultural land [51], and (ii) they produce nectar and pollen. Perennial flowering industrial crops such as cup plant, Virginia mallow (Figure 1e), willow and black locust (*Robinia pseudoacacia* L.) are even more promising due to their better environmental performance than annual crops [157–159]. However, the potential effects of perennial bioenergy crops on the existing agroecosystems should also be considered, especially in the case of neophytes such as the cup plant in Europe [151] and knapweed (*Centaurea* spp.) in the United States [160]. Since there is little knowledge of the effects of bioenergy cropping systems on pollinators on marginal agricultural land, further research is highly recommended.

2.1.3. Low-Input Agriculture, GHG Mitigation Potential and the Role of Legumes

Bioenergy crops cultivated under low-input agricultural practices [161,162] are of increasing importance in terms of emission reductions. Low-input agricultural practices can be applied in the categories (i) soil tillage, (ii) fertilization (mainly N and phosphorus (P)), (iii) fuel use, (iv) sowing material, and (v) plant protection measures. Once established, perennial bioenergy crops such as miscanthus, Virginia mallow, switchgrass, poplar (*Populus* spp.), and willow have a higher nutrient use efficiency than annual crops [163–165]. This is due to a better developed rooting system and the low demands of these crops for nutrients, water, and other inputs. The resilient nature of perennial bioenergy crops renders them highly relevant for a growing bioeconomy. This is because an efficient use and low amount of N fertilizer is required to significantly reduce agricultural GHG emissions because it reduces the requirements for N fertilizer production, as well as emissions from the soil [91,166–170].

For the outlined reasons and their potential to reduce N fertilizer requirements, the role of legumes and their capacity for atmospheric N fixation are also of great importance for sustainable biomass production and cropping strategies [87,132,171]. Some alternative bioenergy crops such as yellow melilot, lupin, and lucerne [88,108,122] are able to fix atmospheric N through rhizobacteria [132]. Thus, poor soils, such as marginal sandy substrates, can be enriched with non-synthetic N sources and increase the overall productivity of the agroecosystem in a natural way, for example, when intercropped with Virginia mallow as a perennial biomass plant [86]. In this case, a non-leguminous bioenergy crop potentially acts as a cover or catch crop, thus reducing N-leaching in surface and groundwater—as indicated by a recent study on a grain-legume cropping system [172]. However, legume intercropping with bioenergy crops may compete with soil resources—therefore, combining deep-rooting perennial crops and shallow-rooting legumes might be a promising option. Whereas, its practicability requires further validation. It is even possible to optimize legume-based N fixation through precision farming applications, for example, through mapping the field-level spatial variability for air–N fixation activity [173]. This could help to optimize the efficiency of other site-specific fertilization techniques, such as the application of solid manure or digestate. Consequently, the cultivation of legumes for bioenergy purposes will remain highly relevant to the pursuit of more social-ecologically sustainable bioenergy crop cultivation in future.

2.1.4. Groundwater Protection and Nutrient Recycling

The potential of groundwater protection for cropping systems can be explained roughly by its effect on the overall filtration capacity of the topsoil [174–176]. This means that the lower the nutrient leaching and the lower the use of synthetic agrochemicals such as herbicides, fungicides and insecticides, the lower the negative impact of the cropping system on the natural filtration capacity [174].

In Germany, there is a heated debate on when and where to apply how much manure or digestate after the winter period. This is because the manure or digestate tanks are full after winter, and thus need to be emptied quickly in spring. However, there are strict regulations for the maximum application rate (170 kg N ha^{-1} via organic fertilizers, following the German fertilizer ordinance of 2017) because the digestate contains considerable amounts of N (4.2 kg N m^{-3}, [177]) and P (1.7 kg P m^{-3}, [177]). Throughout Europe, the accumulation of manure in dense animal production regions results in a source to sink imbalance of nutrients which cannot always be compensated for via plant biomass production in situ. Consequently, the digestate must be transported over long distances to areas where nutrients are needed. This increases the transport costs and emissions [47,178]. Both of these challenges could be avoided because biogas cropping systems allow for improved on-farm nutrient cycling using separation and extraction techniques [179,180]. This means that it is possible to recover more than 90% of P from the digestates and transform it into fertilizable P-salt [179,181]. This P-salt can either be used as on-farm fertilizer for bioenergy (or food) crop cultivation, or it could be sold as a high value product [179]. After nutrient extraction, the remainder of the digestates have lower contents of N and P. This leads to practical advantages at the farm scale, because higher amounts of digestate can be applied at closer distances to the biogas plant without over-fertilizing, and without increasing the risk of nutrient leaching while the organic matter can still be used for maintaining or improving soil fertility [89].

Cultivating perennial bioenergy crops on marginal agricultural land will require sustainable fertilization strategies allowing for a successful establishment of the crops and a high biomass productivity, while avoiding nutrient leaching and potential aquifer pollution. For example, when cultivating Virginia mallow [182] in marginal sandy soil, digestate fertilization resulted in significantly less N leaching compared with NPK fertilizer but similar biomass yields and an increased soil carbon content, water holding capacity, and soil basal respiration, indicating an improved fertility of the marginal soil [132,183]. Other perennial biomass crops such as giant reed have the characteristic of leaving very low amounts of residual soil nitrate after harvest, which also helps in reducing potential N leaching over winter [184]. In an intercropping system of triticale and clover grass on two marginal sites, separated digestates were able to substitute mineral fertilizer completely in a long-term experiment (longer than six years) without decreasing biomass yield [185]. Moreover, wastewater reuse in the irrigation of perennial crops of giant reed and miscanthus was evaluated as an approach to promote bioenergy cropping systems in water-scarce regions (e.g., the Mediterranean) [186]. Results showed that biomass productivity was not affected and that the soil–plant system retained over 90% of the pollutant load, resulting in wastewater depuration. Additionally, many bioenergy crops, especially perennial crops [166,167,187], require low or even no chemical plant protection measures at all [51,88,122]. Thus, bioenergy crop cultivation on marginal soils, when cultivated with the aid of soil ameliorating biogenic residues used as fertilizers, could contribute to more sustainable biomass production and C storage in the future.

2.1.5. Soil Erosion Mitigation under Steep Slope Conditions

The prevention of soil erosion is a highly relevant issue, especially in the Mediterranean agro-ecological zone (AEZ) [51]. Generally, the risk of erosion is high when steep slope conditions are combined with low vegetative soil cover [188]. Under these conditions, both heavy rain and wind remove the topsoil layers which, over time, leads to a decrease in the rooting conditions. In the Mediterranean AEZ, an area of approximately 62,000 km^2 is covered by sites prone to erosion and, in many cases, subject to further degradation [51,78]. Some wooden and perennial lignocellulosic bioenergy crops, such as miscanthus, giant reed, and other perennial grasses [60], provide the opportunity to cope with steep slope conditions and minimize soil erosion [188–190]. The strip cultivation of annual bioenergy crops can reduce soil erosion by up to 80% [190]—insofar as good agricultural practices are met. Such practices include the timing and type of soil tillage, because the lower the soil disturbance (i.e., minimum tillage, no tillage), the lower the erosion risk. In the Mediterranean area, soil tillage performed in early autumn is highly risky since the soil is not covered by vegetation and the bare soil is subjected to heavy rains, usually occurring from the end of summer. Furthermore, it is important to select both the right amount (and type) of fertilizer and the right time for its application according to each crop in erosion prone sites. In many cases, perennial bioenergy crops require low N and P applications because of their capability to relocate and re-use these nutrients [91,191].

Furthermore, perennial cropping systems can even increase the soil fertility of the erosion affected sites. This is because perennial cropping systems increase the living conditions for soil microbial communities [192], due to less soil disturbance (compared with annual cropping systems), soil organic carbon-enrichment [193], and a lower need for pesticides. This applies to most perennial bioenergy crops, such as miscanthus [163,194], switchgrass [60,195,196], giant reed [172] and willow [197,198]. Conversely, there is no information on the suitability of other perennial crops such as cup plant, Virginia mallow or wild plant species such as common tansy (*Tanacetum vulgare* L.), common knapweed (*Centaurea nigra* L.) and mugwort (*Artemisia vulgaris* L.) [88,122] for erosion prone sites with steep slope. Furthermore, steep slope conditions remain challenging for all agricultural, mechanized management procedures [199–201]. However, we assume that erosion affected sites could be economically and social-ecologically more sustainably utilized through perennial BCS compared with annual crops. In some cases, a terrace-like cropping system (following a basic agroforest approach under steep slope conditions) might enable a multiple use of the site for the simultaneous cultivation of both industrial and food crops [200].

2.2. The Potential Growth Suitability of Bioenergy Crops on Marginal Agricultural Lands

In total, European marginal agricultural land accounts for approximately 640,000 km^2 [51] (Figure 4). The most severe constraint categories are (i) adverse rooting conditions (155,519 km^2), (ii) adverse climatic conditions (112,096 km^2), and (iii) excess soil moisture or poor drainage (108,081 km^2) [51]. The following sub-sections highlight these major biophysical constraint categories of marginal agricultural land and how they could be overcome by adequate bioenergy crop cultivation.

Drought is very relevant for crop production as the amount and distribution of rainfall throughout the growing seasons affect plant growth, development, and yield. Limited amounts of water during plant growth causes water stress, in turn influencing physiological plant responses such as photosynthesis, mainly through stomatal closure to restrict water loss by transpiration [202–204]. Other typical symptoms of water stress include changes in cell growth, leaf expansion rate, and other plant morphological processes [202,205].

Soil moisture availability is a measure of dryness, which depends on the rates of precipitation and potential evapotranspiration. The combination of low precipitation and high evapotranspiration leads to poor crop growth by limiting the moisture supply. According to Van Orshoven et al. (2014) [206], dryness is calculated based on the ratio of annual precipitation (AP) to annual potential evapotranspiration (PET). The threshold value for dryness proposed by Joint Research Center (JRC) is 0.6 ($AP/PET \leq 0.6$) [206,207].

Plants have developed different strategies to cope with drought, such as escape (typical of annual species), avoidance, and tolerance. These adaptive responses can contribute to a sustainable utilization of drought-prone marginal agricultural lands. Some perennial herbaceous grasses combine both avoidance and tolerance. Depending on the drought intensity, they can also apply adaptive responses including resistance to moderate drought with growth maintenance (dehydration avoidance and tolerance of lamina), growth cessation, and the survival of plants under severe stress to regrow at rehydration (dehydration avoidance and tolerance of meristems) [208].

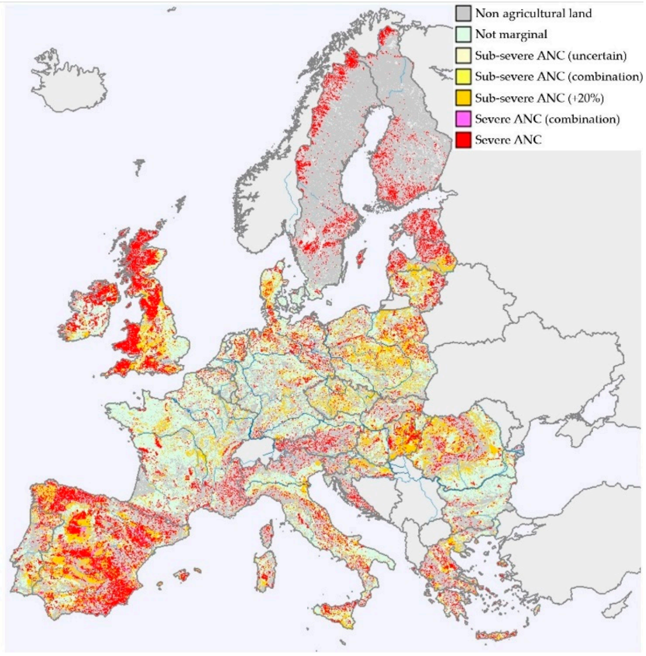

Figure 4. Current distribution of marginal agricultural land (ANC: agricultural natural constraint. Sub-severe ANC + 20% is within the 20% margin of the threshold value of severity) in Europe (adapted from [51]).

The giant reed is one example of an opportunistic water using and drought resistant crop [60]. It is a mesophyte but can either grow in xeric or very humid environments. Efficient stomata regulation to contain water loss, leaf-rolling mechanism to increase the avoidance of dehydration by reducing incident radiation and temperature at the leaf level, and a deep root system explain the efficient water use and tolerance to durable periods of drought [202,209]. On the other hand, drought survival or summer dormancy is associated with some perennial pasture species of minor importance for bioenergy purposes, which however, could be valuable sources under extreme environments [210]. The annual bioenergy crop kenaf is also described as flexible in relation to water availability [211]. It reduces stomatal conductance and transpiration rate when water availability is limited, tolerating drought and being able to recover following re-watering.

Excess soil moisture conditions limit the oxygen supply in plant root zones impeding nutrient uptake [212]. Sub-optimal cultivation systems further increase the risk of disease outbreak and environmental damage through nutrient leaching, GHG emissions, and soil compaction. The mechanisms of both excess soil moisture and limited soil drainage have been concisely explained by Van Orshoven et al. (2014) [206]. Following their conclusions, excess soil moisture should be evaluated by adding up the number of days with soil moisture content exceeding field capacity [206]. The threshold for severe excess soil moisture conditions for plant growth is 230 days [206]. There are several known wooden and perennial bioenergy crops that can cope with severe excess soil moisture conditions, such as willow and reed canary grass [213].

Limited soil drainage is a morphometric parameter indicating soil wetness for a longer period. According to Terres et al. (2014) [207], an indicator for limited soil drainage is a Gleyic color pattern within 40 cm. Both excess soil moisture and limited soil drainage strongly depend on climate (e.g., high precipitation) and geophysical conditions, e.g., landscape and soil type. Under such conditions, perennial BCS, such as willow short rotation coppice, are suitable options [198]. Recently, several perennial crops were also found to be promising for waterlogged sites [214]. Whereas, these results draw on pot trials and need further evaluation under field conditions.

The cultivation of industrial crops in sites with high proportions of clay (>30%) [215] is promising because heavy clay is more or less unsuitable for the cultivation of food crops due to adverse rooting conditions [216]. This means that the potential for land use conflicts between industrial crop and food crop cultivation would be low. However, the cultivation of industrial crops on heavy clay soils is also challenging because of (i) a difficult establishment procedure, e.g., seed-bed preparation [217] (ii) and adverse rooting conditions, i.e., dry soil cracks and damage to the plant roots within the topsoil. This reduces the water and nutrient uptake ability of the plants. Consequently, the aspect of growing perennial industrial crops such as miscanthus [218] and giant reed [219] on marginal agricultural land affected by heavy clay should be further investigated.

Similarly challenging, and yet promising, is the cultivation of bioenergy crops in contaminated soils, especially for heavy metal contaminations [220,221]. Heavy metal contamination applies, if the contents of heavy metals, such as cadmium, zinc, and nickel, are above a certain threshold. In Europe, the Council Directive of 12 June 1986, identifies the limits for heavy metal concentrations in the soil [222]. These limits are meant to protect the environment, especially the soil, when sewage sludge is used in agriculture. The generic term for this type of marginal agricultural land is 'adverse chemical conditions' [51], and more than 22,500 km^2 across Europe are affected [51]. Many bioenergy crops, such as miscanthus and giant reed [223], poplar trees [224], hemp, flax, and kenaf [225], have shown tolerance to heavy metal contamination. The cultivation of bioenergy crops in soils contaminated by heavy metals presents several opportunities. One positive social-ecological effect of utilizing contaminated land for BCS is the phytoremediation of the area: the presence of vegetation may improve soil properties, control soil erosion, and increase biological and landscape diversity and, after a certain period, the area could become available for food crop cultivation again [226]. Yet, yields can be affected by the contamination, as it was observed for sugar beet (*Beta vulgaris* L.) grown in nickel contaminated soils [227]. However, when the level of contamination in the soil is not high enough to induce toxicity, or when the existing contaminants are not bioavailable to be accumulated by the plants, yields may not be affected [228,229].

Furthermore, the accumulation of heavy metals within the biomass value chain (e.g., within the biogas value chain) must be avoided. This could be done by using another utilization pathway such as combustion [182,230,231]. For combustion, the heavy metal content will be highly concentrated within the ashes of the processed biomass. This contaminated ash can be disposed less problematically than contaminated digestate from biogas production, for example. However, the increment of ash material may increase the amount of fused agglomerates and slag deposits, accelerating the metal wastage of furnace and boilers components, thus reducing the equipment's life [232]. Moreover, the yield loss may induce a concentration of elements such as N, increasing N oxide emissions if biomass is combusted [233]. A toolbox to address the technological and environmental constraints associated with the use of biomass for energy from marginal land has been prepared on the basis of current knowledge [234]. According to biomass composition, it is possible to choose the best energy technology for different types of contamination.

2.3. *Climate Change Effects on Agriculture and Adaptation Strategies for Bioenergy Cropping Systems*

This section reports on the projected climate change effects on agriculture [235], and how BCS could contribute to climate change adaptation with respect to low-input systems for biomass production in marginal agricultural land [51].

2.3.1. The Projected Climate Change Effects on Agriculture

Climate is one of the limiting factors for the growth of all plants including bioenergy crops. Growth degree days (GDD), annual precipitation, and drought events are key to determining whether a region is suitable for the cultivation of a certain bioenergy crop [51,206]. Therefore, an adequate estimation of the future growth suitability of bioenergy crops requires a consideration of climate change projections [236–239]. Regional climate model projections in the frame of the Coordinated Downscaling Experiment for Europe (EURO-CORDEX) [240] show significant warming and changes in precipitation in the 21st century. Notably, such changes depend on the radiation concentration pathway (RCP) and region (e.g., [241]). Results show a change in the precipitation statistics (amount, frequency, and intensity) causing more droughts, more wet periods, more rain instead of snow and a shift in the seasonal rainfall patterns in some regions (e.g. [242,243]). The length of the growing season will increase and change the crop's phenological development pattern (crop-specific), thus increasing the vulnerability to late frost events, heat stress, and droughts. Within EURO-CORDEX, an ensemble of CMIP5 global climate model simulations is downscaled to ~ 12 km resolution with an ensemble of regional climate models. To reduce model uncertainty, these climate model ensemble data can be applied to force impact models [244]. For example, the projected change in GDD by the COSMO climate model (CCLM) downscaling the climate data from the EC-EARTH global climate model is displayed in Figure 5. Figure 6 shows the simulated change in precipitation for spring and autumn, which are relevant seasons for bioenergy crop cultivation.

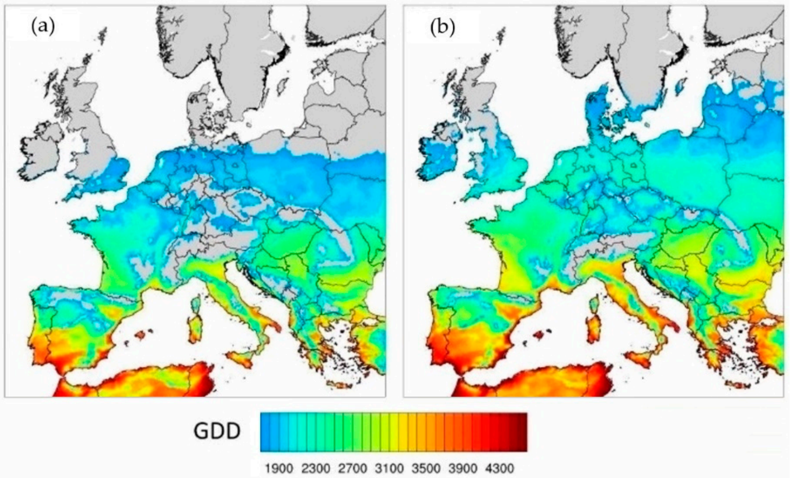

Figure 5. Current (years 1970–2000) (**a**) and projected (years 2070–2100) (**b**) thermal time (in growth degree days, GDD) under the RCP8.5 scenario in Europe. The base temperature is set at 10 °C which applies to the requirements of C4-crops such as miscanthus (*Miscanthus* × *giganteus* Greef et Deuter) and maize (*Zea mays* L.).

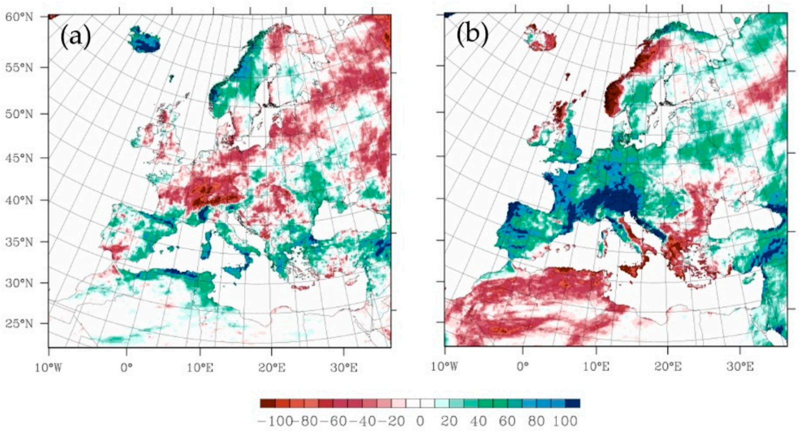

Figure 6. Projected changes in precipitation during the seasons March–May (**a**) and September–November (**b**) until 2050 given a RCP8.5 scenario. Data based on EC-EARTH–CCLM output.

2.3.2. The Potential Contribution of Bioenergy Cropping Systems to Climate Change Adaptation

Generally, the selection of the most suitable bioenergy crop for marginal agricultural land [51,52,82,245,246] will become even more relevant in terms of climate change adaptation, because severe changes in the basic climatic growth conditions are to be expected. This means that some bioenergy crops which are suitable for a certain area of marginal agricultural land today, e.g., contaminated soil, will not be suitable in the future, because the climatic growth conditions will become unsuitable. In large parts of France, Germany, and Hungary for example, there is a projected decrease of precipitation in spring and a projected increase of precipitation in autumn (Figure 6). Here, the rainfed growth conditions will become more challenging for annual bioenergy crops in the future, even though the annual precipitation shows no significant changes (not shown). This is because the changes of precipitation in spring (Figure 6a) affect the soil moisture conditions for the establishment procedures such as seedbed preparation and sowing of annual bioenergy crops. Changes of precipitation in autumn (Figure 6b) are relevant for the harvest management of those bioenergy crops harvested in autumn, such as maize, cup plant, biomass sorghum, and camelina. Most perennial BCS will be more promising than annual BCS in these regions in the light of climate change adaptation. This is because perennial BCS are less demanding in terms of soil tillage in the long term, and they can be harvested in winter when the topsoil is frozen, or at least less saturated than in the autumn. The opposite pattern (an increase of precipitation in spring and a decrease in autumn) is seen in Norway, eastern Italy, and Greece (Figure 6). Here, crop rotations with annual and biennial bioenergy crops may become more favorable in the future. Hence, it is to be expected that site-specific BCS may contribute to climate change adaptation on marginal agricultural land [51].

Furthermore, the projected increase of atmospheric CO_2 of above 800 ppm by the end of the 21st century (RCP8.5) [80,247] is also expected to cause a great shift in the photosynthetic limitations of the bioenergy crops in terms of their photosynthetic pathways (C3, C4, CAM) [248,249]. This means that bioenergy crops with the C3-metabolism [51] are expected to become more relevant in warm regions than those bioenergy crops with the C4-metabolism [51], because the active CO_2-assimilation of C4-metabolism [250] may become superfluous due to the expected increase of atmospheric CO_2 concentrations [248,249]. However, the most important climate change effects to be addressed by well-adapted BCS will be the increased frequency and dimension of drought events [238,239,251].

Therefore, another climate change adaptation strategy that might be relevant for BCS on marginal agricultural land located in regions prone to increasing drought and heat events could be the use of agro-photovoltaic (APV) systems [252,253]. The idea is to shade the ground area with photovoltaic panels, which generate electricity and reduce the soil evaporation potential. A lower evaporation may lead to a higher soil moisture, and thus to a better water use efficiency by the bioenergy crops [252]. Consequently, both the erosion potential of, and the heat stress for bioenergy crops could be reduced underneath APV systems. However, the construction costs for APV systems are very high [252]. Therefore, which bioenergy cropping system to integrate to the APV system requires careful consideration. This is because the net-profit from both the electricity generated and the agricultural produce must compensate for the high construction costs of the APV system. Besides high-value crops, such as oil crops, perennial lignocellulosic crops could be suitable because their production costs are low—as far as low-input practices are considered [51,254]. Either way, both site-specific biophysical conditions and social-ecological requirements should also be taken into account to develop optimized APV system solutions. Thus, further thorough investigations of the effect of APV systems on the microclimate within the plant stands of BCS, in particular at the large scale, are highly recommended.

Additionally, BCS-related climate impacts should also be considered, since land use-change can affect local climate due to cropping-system-related changes in land surface albedo effects [255] or wind speed [256]:

(1) Albedo effects could be induced by perennial BCS harvested in winter or spring, such as miscanthus and switchgrass, because the soil of these BCS is covered with senescence and thus brightly colored biomass during winter.
(2) Wind speed can be reduced by perennial BCS with wooden crops such as agroforestry systems [117,118,257]—this helps to reduce wind erosion and increase the biomass yield [256].

Crop diversification, by means of implementing (perennial) bioenergy crops into existing farming systems, is also a relevant strategy for small-scale family farmers in countries of the south to (i) adapt to climate change and (ii) improve access to modern and clean energy, and thus (iii) improve living conditions.

2.4. Fostering Rural Development and Sustainable Rural Livelihoods

Decentralized bioenergy production is a major driver for increasing access to modern, clean, and affordable energy, in particular in rural areas in countries of the south [22,66,258–260]. In these areas, almost 1 billion people lack access to electricity, while 2.7 billion rely on traditional biomass (e.g., firewood), kerosene, or coal for cooking [22].

The Food and Agriculture Organization of the United Nations regards the integration of renewable energy production into rural smallholder farming systems as vital for the provision and sustenance of rural livelihoods and the sustainable improvement of agricultural production systems [261]. 'Integrated Food and Energy Systems' (IFESs) are based on the principles of sustainable production intensification [261]. Agricultural productivity is maximized through high agrobiodiversity while maintaining the productive capacity of the overall land-use system. Among renewable energy technologies (RET), biodigestion has the advantage that, in addition to energy production, it can help to close nutrient cycles in agricultural systems. An example of an IFES is the 'livestock-biogas-fruit system' developed in Guangdong, South China [262]. Orchard residues and pig manure form the feedstock for biodigesters located under the pig stables. The digester provides biogas as a clean energy source and organic fertilizer. The latter, in turn, improves soil fertility and reduces mineral fertilizer inputs. Further, chickens roam in the orchards, feeding on weeds and pests, decreasing pesticide application and, additionally, providing manure for biodigestion [262].

China is a country with an increasing number of biogas plants. The roll-out of decentralized biogas production started more than a century ago with the aim of increasing energy security in rural areas. The development peaked during the 1970s and resulted in the installation of about 43 million digesters by 2013 [263]. Today, Chinese energy development policies still focus on biodigestion. The aim is to increase biogas production from 16 Gm^3 in 2013 to 44 Gm^3 by 2020, also including centralized large-scale biodigesters [263]. India followed from the 1980s onwards with the National Biogas and Manure Management Programme, leading to the successful installation of 4.75 million biodigesters by 2014 [264] (Figure 7).

The planning and implementation of best–adapted marginal agricultural land low-input systems (MALLIS) need to take local communities, household needs, people's assets, as well as the local natural resource base into account [51]. In addition to technical feasibility and economic performance, locally relevant social aspects need to be considered [66], including: acceptance and trust of new technologies and cropping systems; participation in planning and decision making [265]; gender relations; levels of education, skills and knowledge [266]; poverty level; food and nutrition security [258]; access to clean water [267]; land-use patterns [268], and work load [269].

Figure 7. Household biodigester (**a**) Deenbandhu Model: (1) inlet filled with manure and water; (2) underground fixed-dome fermenter, and (3) outlet chamber in the rural village of Ghoragachha, West Bengal India. (**b**). Women cooking on a biogas stove, directly connected with the biodigester.

The 'Integrated Renewable Energy Potential Assessment' (IREPA) approach provides a holistic and participatory tool for assessing the local appropriateness of bioenergy technologies and designing the respective bioenergy crop cultivation system [66]. With IREPA, the local renewable resource base and people's livelihoods are explored. Based on that, RET are planned according to the available resource base and the role of energy in people's (farming) lives [66]. The application of IREPA identified household biodigesters among the most appropriate options for implementation in a rural community in South Africa and two rural villages in India [66,260]. The major benefit expressed by the interviewed farmers is the ability of a biodigester to produce energy and fertilizer at the same time. The farmers in the Indian case study could not afford mineral fertilizers and had to improve soil fertility by increasing soil organic matter content after decades of intensive production [260], while farmers in South Africa had very limited access to mineral fertilizer due to affordability constraints and poor infrastructure [66].

Bioenergy-based MALLIS [51] are a promising option for the creation of regenerative agricultural systems. Biodigestion is an incentive for farmers, in particular in countries of the South, to collect biomass (including dedicated bioenergy crops, agricultural residues, weeds, organic household wastes, animal manure, and human feces), channel it into the digester to obtain biogas, and to bring the 'digested biomass' back to their fields as organic fertilizer. Closing natural resource cycles on a local level, and thus mimicking natural processes, is a major driver for the sustainable intensification of agriculture which, in turn, fosters the creation of sustainable livelihoods [32].

Furthermore, circular agricultural production systems are also very suitable for urban farming. In cities, huge amounts of organic waste are created, offering enormous potential for urban food production. A very elaborate example is the 'Food-to-waste-food' system of Stoknes et al. 2016 [270] whereby edible mushrooms and vegetables are nourished solely by organic wastes, treated through vermicomposting and biodigestion in a bubble-insulated greenhouse. This novel circular food system showed that organic waste provides enough energy for the operation of the greenhouse (light, heat, pumps, etc.) and, at the same time, sufficient amounts of nutrients for intensive vegetable production [270] in urban environments.

Consequently, biodigestion is a key technology for circular agricultural production systems, in rural as well as urban areas. The major advantage of this technology is the decentralized production of valuable fertilizer by channeling organic waste streams into the digester and, from there, back into the agricultural system. The biogas produced is just a by-product—albeit very valuable.

3. Chances and Challenges for a More Holistic Evaluation of Bioenergy Cropping Systems

Many opportunities and strategies are presented above that are expected to enable more social-ecologically benign and yet productive bioenergy crop cultivation. This is required to contribute to a growing bioeconomy without impeding any SDG in the future. However, in order to guarantee this, a holistic *ex ante* evaluation of the sustainability of various BCS is indispensable. Hereby, not only the environmental performance of the respective BCS must be taken into account, but also the positive and negative socio-economic impacts on the region. The Life Cycle Assessment (LCA) technique is an internationally recognized methodology to assess the environmental impacts of products or services over their whole life-cycle [271]. The LCA methodology is widely used to analyze the environmental performance of various BCSs on marginal land, such as miscanthus, giant reed, switchgrass, or cardoon [24,272–275]. The results of these studies demonstrated, that the use of perennial crops often shows a more favorable environmental performance compared to conventional annual bioenergy crops and in several impact categories also compared to a fossil reference [52,91]. However, even though LCA is widely used, several aspects are still missing, which would be of particular importance for the assessment of the BCSs on marginal land discussed in the current study. Herewith, especially soil quality [276] and the impact of different agricultural systems on the biodiversity [277] are crucial aspects that are not fully included in the current methodologies. In addition, it is crucial to assess whole crop rotations, however, currently, often only the environmental performance of individual crops is analyzed [278]. This is especially true for the BCS which include intercropping and the use of legumes.

As mentioned above, besides environmental considerations, economic aspects also play a major role in the holistic evaluation of different bioenergy crops. Many studies, which compare the economic performance of bioenergy and fossil energy sources, have only assessed the direct costs, excluding externalities. As a consequence, the costs of fossil products are often underestimated, whereas those of biobased alternatives are overestimated. One example of such an externality is the emission of CO_2. In the European Union, the price per European Emission Allowances currently stands at around 29 € t^{-1} CO_2 [279]. However, the German Environment Agency (UBA) estimates the real environmental costs per ton of CO_2 at around 180 Euro [280]. This constitutes an immense indirect subsidy for emission-heavy industries, such as that of fossil-based energy generation. Another example would be ecological services, such as pollination, which positively correlate with both crop diversity and perennialism [139,281]. Pollination for example is a very important ecosystem service with a significant economic impact [282]. Several perennials such as wild plant mixtures have a positive influence on pollinator populations [283]—however this impact is not accounted for on an economic basis. This emphasizes the importance of the integration of environmental and economic aspects. Therefore, either the environmental impacts have to be monetized and thus internalized [284] or a combined assessment of the economic and environmental performance have to take place. In recent years, more assessments have come to include, as well as an environmental assessment, an economic evaluation of the BCS under study [52,285] in order to provide a more holistic picture. In addition to the economic aspect of the introduction of novel BCSs, social aspects must be included. For example, the landscape aesthetics of different BCSs have a significant impact on the acceptance of different stakeholder groups [286].

Consequently, it is crucial to analyze the socio-economic performance of these novel BCSs in addition to the environmental performance before their application on marginal land. One technique to evaluate the economic, social and environmental performance of the various BCSs holistically is the life-cycle sustainability assessment (LCSA) approach [287]. In the framework of an LCSA a Life Cycle Assessment (LCA) is conducted to assess the environmental impacts, and a life cycle costing (LCC) approach is used to evaluate the economic performance. The social impacts on various stakeholders are assessed by applying a social life cycle assessment (SLCA) [287].

4. Conclusions

Bioenergy cropping systems provide a number of promising options for a growing bioeconomy, under the premise that site-specific social-ecological factors are carefully taken into account during planning and implementation phase and in agronomic management. Aspects that need to be considered at the planning stage of BCS include: previous or alternative land use, field size, duration of cultivation (annual, perennial), agronomic practices (e.g., timing and type of soil tillage, amounts of fertilizer and pesticides), and crop-specific characteristics such as the depth of the root system, water and nutrient use efficiency, and its ability to cope with biophysical constraints.

The conversion from annual to perennial bioenergy crops tends to be advantageous for biodiversity and soil fertility. Perennial crop cultivation in corridors in between fields connects habitats, increases landscape heterogeneity and thus fosters the provision of ecosystem services. Intercropping, polyculture and agroforestry also increase agrobiodiversity by cultivating bioenergy crops in combination with food or fodder crops.

Further, perennial bioenergy crops that require low levels of agricultural inputs (tillage, fertilization, and plant protection) are preferential. Examples of perennial crops with relatively low demands and high nutrient-use efficiency include miscanthus, switchgrass, giant reed, Virginia mallow, common tansy, common knapweed, mugwort, poplar, willow, and black locust. The latter is a leguminous bioenergy crop that fixes atmospheric N through bacterial activity and can naturally improve the productivity and efficiency of the overall BCS. Intercropping diverse perennial BCS with legumes also offers the opportunity to reduce N leaching into surface and groundwater bodies which, for example, also supports compliance with the EU water framework directive. In addition, BCS on slopes reduce soil erosion, and thus nutrient losses.

Moreover, biogas cropping systems can improve on-farm nutrient cycling. Modern separation and extraction techniques enable P-salt recovery from biogas digestate, providing relief from nutrient surpluses, especially in regions of dense animal production. As biogas digestate has considerably lower P and N contents after P-salt recovery, larger amounts of the digestate can be applied on-farm, thus reducing the transport of this organic fertilizer with relatively low nutrient concentrations to other areas.

The establishment of BCS on marginal agricultural land reduces competition with the continuously growing demand for food production. For example, soils with a clay content exceeding 30% are often considered unsuitable for annual food crops, due to adverse rooting conditions for the crop and adverse management conditions for the farmer (inaccessible for machinery when wet and untillable when dry). On marginal agricultural land however, bioenergy crops that are able to cope with the given biophysical constraints need to be selected. For instance, willow is suitable in areas with (periodic) water logging, while giant reed is suitable for areas that are periodically waterlogged and at the same time drought prone. BCS are also potentially suitable for the phytoremediation of contaminated soil. Crops dedicated to combustion may take up heavy metals. These metals become concentrated in the ash at a later stage and can be disposed of safely.

The careful selection of bioenergy crops becomes even more relevant in view of the projected effects of climate change. The winter harvest of perennial bioenergy crops is an agronomic advantage in regions with a predicted increase in precipitation in autumn, the harvest period of many annual bioenergy crops. Perennial bioenergy crops with better established root systems tend to be preferential in areas becoming more prone to drought. In such regions, another promising option is the shading of crops to reduce soil evaporation, e.g., by intercropping herbaceous species with woody species to establish agroforestry BCS. Agro-photovoltaic systems are also suitable for the shading of crops and soils and have the advantage of decentralized electricity generation.

Decentralized energy production provides an additional or alternative income source for farmers in rural areas. In countries of the South, integrated food and energy production systems offer rural areas increased access to modern, clean, and affordable energy. The governments of India, and in particular China, have been advocating household biodigesters as a rural energy source for decades.

This provides a major incentive for farmers to channel organic residues, wastes, and manure through the biodigester to obtain both biogas as an energy source and organic fertilizer for their agricultural fields. In these areas, bioenergy can accelerate the creation of circular integrated food and energy systems with a high crop diversity, productivity and efficiency.

The careful integration of the site-specific selection of perennial bioenergy crops can diversify and hence support agricultural farming systems worldwide by: (i) increasing biodiversity and thus ecosystem services, (ii) improving soil fertility, nutrient cycling, and thus productivity, (iii) enabling productive utilization (and restoration) of marginal land areas, (iv) creating additional income and supporting income diversification in rural areas, (v) increasing access to modern, clean and affordable energy, and (vi) aiding resilience and climate change adaptation.

In light of this, it is highly recommended that both further research activities (e.g., biomass potential analysis, implementation, and cultivation guidelines) and policy incentives (e.g., subsidies and greening measures) should not only consider the economic potential of bioenergy crop cultivation, but also aspects of biodiversity, soil fertility, and climate change adaptation, specific to the site conditions and given social context at the local to regional scale. A strong interdisciplinary network of agronomists, ecologists, economists, and farmers is required to ensure a holistic view of how perennial low-input bioenergy crops can be integrated and cultivated on (preferably marginal) agricultural land, and how existing agricultural systems can be adapted in a changing world to foster the development of a social-ecologically more sustainable bioeconomy.

Author Contributions: Conceptualization, M.V.C., V.V.C., K.W.-S., B.E., I.L. and B.W.; methodology, M.V.C., V.V.C., K.W.-S., B.E., I.S., M.V.E., S.H. and Y.I.; software, V.V.C., K.W.-S., B.E., I.S., M.V.E.; validation, M.V.C., K.W.-S., B.E., D.S. and I.L.; formal analysis, M.V.C., K.W.-S., B.E., I.L., N.D.J., M.W., J.L., E.M., A.B. and B.W.; investigation, M.V.C., M.W., J.L., E.M., A.B., V.V.C., K.W.-S., B.E., I.S., M.V.E., Y.I., N.D.J., A.L.F., D.S., S.L.C., V.W., I.L. and B.W.; resources, B.E., I.S., M.V.E., K.W.-S., V.W.; data curation, M.V.C., V.V.C., K.W.-S., B.E., I.S. and M.V.E.; writing—original draft preparation, M.V.C., M.W., J.L., E.M., A.B., V.V.C., K.W.-S., B.E., I.S., M.V.E., Y.I., N.D.J., S.H., A.L.F., D.S., S.L.C., V.W., I.L. and B.W.; writing—review and editing, M.V.C.; visualization, M.V.C., V.V.C., K.W.-S., B.E., I.S., M.V.E. and B.W.; supervision, B.E., I.L., N.D.J., A.L.F., S.L.C. and V.W.; project administration, M.V.C., M.W., J.L., E.M., A.B., V.V.C., K.W.-S., B.E., I.S., M.V.E., Y.I., N.D.J., S.H., A.L.F., D.S., S.L.C., V.W., I.L., B.W.; funding acquisition, B.E., A.L.F., D.S., S.L.C., and I.L.

Funding: This research received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727698 and the University of Hohenheim. N.D.J. received funding from the Bioeconomy Science Center (BioSC), supported in the project AP3 Focus Lab. The scientific activities of the Bioeconomy Science Center were financially supported by the Ministry of Innovation, Science and Research within the framework of the NRW Strategieprojekt BioSC (no. 313/323-400-002 13).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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